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Impact of Pavement Defects on Motorcycles' Road Safety

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Abstract

Degradation of the pavement has a significant impact on road safety and, in particular, asphalt polishing turns out to be very hazardous for powered two wheelers. The paper reports the results of a study aimed at analysing the effects of asphalt polishing of pavements on the dynamic behaviour of motorcycles. A dynamic simulation code was used in order to understand the motorcycles dynamics parameters in different conditions, define a model of the dynamic behaviour of motorcycle and propose a useful tool for planning maintenance interventions based on the risk associated to the asphalt polishing of the pavement.

Keywords: road safety; road damages; asphalt polishing; maintenance; motorcycles

1. Introduction

All over the world the number of motorcycles registered powered two-wheelers (PTW) are constantly increasing. Especially in the European Union the number of motorcycles has risen up from 16 million in 2001 to more than 22 million in 2008 [1]. The powered two-wheelers differ from other motor vehicles in several features: first of all they have only two points of contact with the pavement, contrary to cars and other four wheels vehicles, which makes them less stable; the engine of a PTW has a relatively high power compared to its mass and this allows a greater acceleration compared to cars; the motorcyclist is relatively more vulnerable because of the lower protection in case of impact and the lower visibility to other motorists. These characteristics and others make PTW very vulnerable and a crucial topic for road safety analysis above all considering the great impact of motorcycles accidents on the total amount of crash data.

The probability to become involved in a fatal accident is much higher for motorcyclists than for other drivers. According to the recent 5th Road Safety PIN Report of the European Transport of Safety Council [2] on EU roads

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a total of 170,000 pedestrians, cyclists and powered two-wheeled (PTW) riders have been killed since 2001, 15400 of them in 2009. Deaths among this category of unprotected road users have been decreasing at a lower rate than for vehicle occupants. Deaths among pedestrians and cyclists decreased on average by 34% between 2001 and 2009 and those among PTW riders by only 18%, compared with 41% for vehicle occupants. At least 42500 riders were seriously injured in road collisions in the year 2009 alone. While the number of road deaths has declined considerably in the past decade in Europe, the number of PTW riders killed rose in 13 out of 26 countries. This rise can be attributed only partly to the increase in use of PTWs and should urgently receive special attention from policy makers at the national and European levels. Moreover PTWs killed represent 17% of all road deaths and big disparities exist between countries. In example in Italy the scenario is rather critical especially in metropolitan area [3]. Although motorcycles represent a lower percentage (13%) of vehicles involved in road crashes related to passenger cars (68%), they count for more than 27% of all road deaths.

Finally according to Huth et al. [4] the types of crashes with the involvement of motorcycles differ from the crash configurations of other road users. The most frequent type is the single-vehicle motorcycle crash outside urbanized areas, where the rider runs off the road at a relatively high speed, representing up to 27% of all motorcycle crashes [5, 6]. Especially in such cases the state of road pavements could play a crucial role in the occurrence of a motorcycle crash. Several literature studies investigate motorcycle safety (e.g. [7-9]) and some of them have analyzed the topic sharing crash responsibilities among vehicle, human factors, environmental factors and road [1, 10-12]. More specifically some authors agree that the deterioration of road pavement has a significant impact on road safety (e.g. [13, 14]). One of the most complete and extensive research on two-wheeled vehicles incidental causes [1] has identified a significant percentage of accidents caused by structural defects of the pavement which are often a cause of improper or delayed maintenance.

Generally literature agrees that pavement conditions deeply affect safety [13-15]. A significant percentage of accidents are caused by surface deformations, cracks and potholes that induce unexpected acceleration on the vehicle, that simultaneously reduces the available friction between the tires and the pavement and increases the needed friction [11]. In other cases the damage produces some dangerous deviation of the trajectory or loosing of control. Preliminary work to understand when, where and how single damage becomes very critical for vehicle safety has been developed in the recent past using numerical simulation (e.g. [15]). The actual challenge is to draw up a framework with the relationship between different kinds of road defects and unsafe driving condition taking into account that the damage consequences on safety strongly depend on the stage of the evolution of the damage itself.

Actually, all over the world, the pavement management takes into account only economic and financial approaches neglecting safety criteria. The main objective of the current research, according to the most advanced researches that have not yet found a practical solution, is to integrate in the pavement management some principles for preventing road accidents or for mitigating the final effects. However there are not detailed researches aimed to study how several factors of damage of the pavements potentially affect the accidents of powered two-wheelers. The probability of accident occurrence while driving on a damaged road depends on different factors: the severity of damage, the position of the damage (geometric element on which the damage is located and displacement on the cross section), the speed of vehicle.

Under this perspective a more comprehensive full study on the evaluation of road safety based on road pavement damage characteristics has been developed for several years by the research team of the Interuniversity Research Centre of Road Safety (CRISS). First studies demonstrated that as the pavement quality decreases the risk for vehicle increases, showing different cases depending on the nature and the evolution of the specific damage (e.g. [11]) demonstrating that it could be very useful to know how risk level increases during the time and the evolution of damage, and which is the maximum risk level that takes into account safe driving conditions. Other studies were carried out in order to establish and evaluate indicators able to identify the level of risk associated with road damages [11, 15]. Parameters and thresholds proposed strictly depend on different factors and it is not possible to generalize them unless considering the specific situation. Recently Bella et al. [15] began to analyse the safety of driving on damaged road with specific reference to a category of unprotected road users: powered two-wheeled riders. The authors investigated the correlation between the safety condition of motorcycle dynamic and road pavement damages, with specific reference to potholes on pavement surface. Specifically, studying the different characteristics of potholes and road geometries that mostly affect the safety of driving (dimension of potholes, localization of potholes along with the road geometries, density of potholes, weather conditions, vehicle speed), the authors proposed several predictive models based on the variables investigated and some diagrams that could be used for evaluating the risk level of different driving conditions characterized by the presence of potholes on road surface.

In order to enlarge the previous research on other pavement defects such as road potholes, the present study focuses on another type of damage: the asphalt polishing of the aggregates. This is one of the most frequent damage whose evolution can be really dangerous especially in relation with the equilibrium of powered two-wheelers. In fact the asphalt polishing may be reflected in a reduction of surface friction. The skidding resistance of a road pavement (concrete or bituminous) depends on the type and depth of the surface texture and the resistance of the aggregates in the surface of the slab, to polishing and abrasion. The reduction of skidding resistance results in the loss of surface texture and polishing that is caused by the action of traffic on the surface, and particularly occurs in the wheel tracks and in areas of heavy traffic trajectories or where high stresses are achieved between surface and tires.

2. Research Objectives

This study was aimed at analyzing the dynamic response of a motorcycle when it runs on an asphalt polished road surface located along a curve with different radii and under different values of speeds. The main objective of the present investigation, that is consistent with previous studies [11, 15], is to define useful tools which could be used by the authority to plan the maintenance of the pavement in order to improve road safety. More specifically the objectives of the paper consist in:

- Defining predictive models of the most significant variables that affect the dynamic behaviour of motorcycles related to the features of the polishing, the radius of the curve where polishing is localized and the speed of the motorcycle;
- Proposing useful tools for planning maintenance interventions based on the evaluation of the risk connected to different configurations in terms of severity of damage, radius of curve and motorcycle speed.

For these aims BikeSim dynamic simulation code [16] was used. Such simulation code provides accurate methods for simulating the dynamic performance of motorcycles. The dynamic simulation codes have been demonstrated to be a useful and effective way to study the dynamic behaviour of the motorcycles which is induced by features of pavement [17, 18]. Several researches aimed at analyzing the influence of pavement characteristics, as roughness, road defects and road geometry on wheel-road interaction [11, 15, 19] using BikeSim dynamic simulation code have been carried out with outstanding results.

Finally the methodology proposed here could represent both a safety based decision support system for pavement management and a strategic tool to identify priorities and best rehabilitation planning.

The study is developed following several steps and duplicating the procedure developed in previous studies [11, 15] in order to improve and enlarge the results of the whole research:

- Experimental design: definition of the variables characterizing scenarios configurations: damage level of polishing, their localization on curves with different radius, speed of motorcycle along the curve;
- Dynamic simulation: implementation of the scenarios in the dynamic simulation code, test and data collection;
- Data analysis: development of predictive models for the variables that affect the dynamic behaviour of motorcycle and proposal of tools for planning maintenance interventions.

3. The Experiment

All tables should be numbered with Arabic numerals. Headings should be placed above tables, left justified. Leave one line space between the heading and the table. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which authors may find useful. The present study enlarges the findings of the previous research investigating another asphalt defect, the polishing of aggregates, characterized by different friction levels, under different condition of road geometry, speed of motorcycle and braking force along the curve. The asphalt polishing represents a great hazard for driving safety especially for powered two wheelers. According to the most important international distress identification guides [20-24] it is caused by the action of traffic on the road surface, and particularly occurs in the wheel tracks and in areas of heavy traffic trajectories or where high stresses are achieved between surface and tires. Moreover it can reach different severity levels during the design life of the pavement and consequently cause, above all, serious reduction of surface friction.

As a consequence several levels of friction were considered in the study, in order to simulate the typical consequences of asphalt polishing on roads pavements characterized by different severity of the damage. Moreover the effects of the same polishing severity (μ) on road safety (expressed here with the motorcycle stability) was investigated under different driving conditions characterized by 1) geometrical features (R, the radius of the curve where the polishing was localized), 2) the cinematic of the motorcycle (V) and 3) severity of the braking action (F) of the rider along the curve. As a consequence a lot of different configurations were considered in order to understand how the polishing could affect the equilibrium of the motorcycle in the critical situation of a sudden braking manoeuvre along a curve.

3.1. Apparatus: the simulation code

As mentioned above, the dynamics simulation code used in the study was BikeSim® [16]. It is a commercial vehicle dynamics simulation software which simulates the dynamics of the vehicles through accurate mathematical models. This software is characterized by a high computational speed, very intuitive interface and an open architecture able to manage multiple variables.

The vehicle selected for the simulations, among the several vehicles inside the software database, was similar to a well-known model of Triumph, called Bonneville (Figure 1), both for the physical and structural characteristics and the mechanical performances.

In order to study the effects caused by pavement defects on the stability of the motorcycle, the following driving parameters (shown in Figure 1) were recorded:

- three components of the acceleration applied to the mass centre of the motorcycle: lateral (A_y), vertical (A_z) and longitudinal (A_x);
- three components of the rear tire force: lateral (F_y), vertical (F_z) and longitudinal (F_x);
- three components of the front tire force: lateral (F_y), vertical (F_z) and longitudinal (F_x);
- destabilizing moment on the front tire (M_x);
- lateral position (trajectory) of the motorcycle respect the lane axis

The analysis of all the forces and destabilizing moment observed in each configuration will be discussed in a forthcoming paper. Here the authors have analyzed especially the trajectory of motorcycle along the simulation as it will be discussed later in the paper.

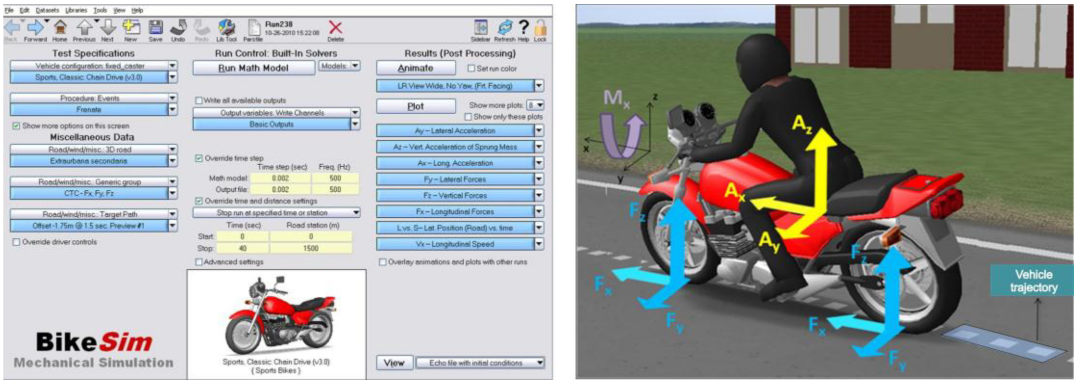

Fig. 1. BikeSim software interface (on the left) and outcomes of simulation (on the right)

3.2. Independent variables

3.2.1. Friction levels (μ)

More in depth tire and vehicle characteristics were selected in the BikeSim software: tire dimension, deflection, rolling resistance, shear forces and moments for the tires, motorcycle dimensions and geometry, sprung and un-sprung masses, inertia moment for the vehicle were defined in the simulation code and kept constant for all the simulations.

The evolution of polishing with time was represented in the study through different values of friction coefficients that corresponded to different level of severity of the damage ranged continuously between 0.3 (high severity of polishing) to 1 (no polishing).

3.2.2. Geometries (R)

The alignment of the road implemented in the simulation code used for all the tests consisted in an approach tangent, a clothoid, and a circular left curve followed by an exit clothoid and a final tangent. Three curve radii were investigated in order to simulate different geometric conditions: 200, 300 and 400 meter. The lengths of both tangents were 100 m while the length of the horizontal curve depended on the selected radius. The transversal slope of the road pavement was considered according to the Italian technical rules. The tests were carried out using a constant speed for each horizontal feature, excluding the braking manoeuvre phase where a constant deceleration was applied. The cross section of the road consisted in a single lane 3.5m wide.

3.2.3. Braking force (F)

The braking manoeuvre is one of the main actions that a rider repeats several time along a ride. The severity of the braking action (brake force) strictly depends on several variables, such as traffic flow conditions, emergency actions, etc. In order to simulate the most common driving conditions, different levels of braking action, characterized by different braking forces, were considered for the tests. In particular three different values of braking force were used according to the values of applied strength on the brake lever evaluated through telemetry surveys: 80 N (corresponding to a soft braking manoeuvre), 120 N (medium braking force) and 160 N (simulating an emergency manoeuvre). The braking action was achieved starting at the beginning of the circular curve in order to simulate the most critical dynamic condition.

3.2.4. Motorcycle's cinematic (V)

The cinematic of the motorcycle was studied under different configurations. First of all different values of initial speed along approach tangent were considered (100 km/h, 120 km/h, 130 km/h). Later at the beginning of the circular curve a braking action (characterized by different braking forces F) was adopted in order to reach different final speeds (V) along the curve, depending on the radius R: between 75 km/h and 95 km/h for R=200 m; between 85 km/h and 105 km/h for R=300 m; between 105 km/h and 115 km/h for R=400 m. At the end of the braking action the motorcycle carried on to ride with the final speed (V).

3.3. Scenarios configurations

A lot of scenarios/configurations were implemented in the simulation code according to the several combinations of variables previously discussed. In example for each value of radius the selected motorcycle speeds, brake actions and all the coefficients of friction were cross-used for an amount of more than one hundred configurations/scenarios. A first phase of the study was aimed at verifying if the motorcycle, under the specific condition of the configuration, fell or did not fall in order to identify those configurations (in terms of μ, R, V and F) that cause the loss of stability of the motorcycle. Among the studied configurations cannot be considered "safe" all those which do not cause the fall. That because motorcycles that do not fall are, however, subjected to high dynamic effects that can determine risk conditions. For this reason a second phase of the analysis was performed in order to obtain for each configuration a risk evaluation using a risk indicator based on the trajectory of the motorcycle recorded during the dynamic simulation.

4. Results and Discussion

4.1. Phase 1: preliminary analysis and results

In this section the preliminary results of the simulations performed over the configurations are briefly summarized. For different scenarios characterized by the combinations of horizontal curve radius, friction coefficient, longitudinal speed of the motorcycle along the curve and braking force, a threshold of safe condition was identified according to the dynamic behavior of the motorcycle under each specific configuration. Specifically the safe condition was defined when the motorcycle carried on the ride after the braking action along the curve, while the unsafe condition occurred when the motorcycle fell down along the simulation. For all the different conditions simulated it was possible to draw a diagram for each radius (R) and braking force (F) adopted as a function of friction coefficient (μ) and motorcycle speed (V) as illustrated in the example in Figure 2 for R= 200 m, F= 160N. While in some configurations the equilibrium of the motorcycle was preserved (see the no fall area), in other configurations the forces achieved on the vehicle did lose the dynamic equilibrium and the motorcycle fell down (see fall area). The "fall threshold" is represented in Figure 2 by a red line that divides the fall area from the no fall area. It is a "critical threshold" that represents the limit combination between speed and friction coefficient that causes the instability of the motorcycle and it falls down under the combination of the variables R and F considered. As shown in Figure 2, the speed decreases as the friction coefficient decreases.

Obviously several diagrams were realized for all the simulated values of horizontal curve radius and braking force. The realized diagrams provide the combinations of friction coefficient and motorcycle speed that determined the fall of the vehicle under each combination of radius and braking force.

These diagrams could be used as an application tool by managing agency in order to identify the priorities of the maintenance interventions in relation to the risk of falling down for a motorcycle that runs with a specific speed in a road characterized by a friction coefficient (polishing damage).

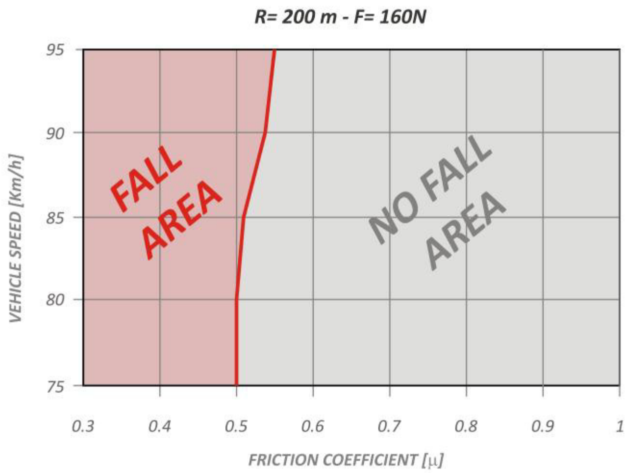

Fig. 2. The safety threshold line in case of R=200m and F=160N

Although an interesting result was found a more in depth analysis was needed. In fact while the “fall area” identifies several combinations of variables (μ and V for each R and F) for which the motorcycle fell and no further analysis are necessary, the “no fall area” identifies the region where the motorcycle does not fall, although it is surely subjected to destabilizing forces that sudden change its dynamic equilibrium and could cause driving safety problems. Consequently we cannot consider "safe" all those conditions which do not cause the fall, but it is needed to evaluate them in order to improve the risk analysis of the study.

4.2. Phase 2: indicator and predictive model

According to the previous considerations, a further analysis was carried out aimed at identifying an indicator of simulation that could take into account the consequences of destabilizing forces on motorcycling dynamic behaviour and stability. According to previous study [11] it was chosen an indicator (S) that take into account the differences between the fixed trajectory of the vehicle (middle of the lane) and its actual trajectory recorded during the simulation. The main hypothesis behind the indicator is that higher S greater the difficulties of the rider to maintain the motorcycle along the fixed trajectory and, as a consequence, greater the impact on the driving safety. The indicator S can be computed using Equation 1:

$$S = \int_{x_0}^{x_1} \delta(x)dx \qquad (1)$$

where:

- $\delta(x)$ is the lateral distance of the motorcycle respect to the target path,
- x_0 is the longitudinal position where the motorcycle begins to deviate from its theoretical fixed trajectory,
- x_1 is the longitudinal position where the motorcycle turns back to its theoretical fixed trajectory

The values of S were obtained for all the studied configurations based on the trajectories of the motorcycle recorded during the simulations. A regression analysis was performed between the indicators S so computed and the independent variables of all the configurations (μ, V, R, F). More specifically a multiple linear regression analysis step by step was performed, checking the following characteristics:

- high value of the coefficient of determination R^2 ($\geq$0.7);
- significance of each independent variable used in the model (the regression coefficient of each independent variable is different from zero at the level of significance *p* of 5%);
- simplicity of the model and logical explanation of algebraic sign of each coefficient of the independent variables.

Among all the predictive models that respected these features it was proposed the following one (see Equation 2) as fit at the best the observed data:

$$S = 7{,}776 - 1{,}203\mu + 0{,}002F + 0{,}03V - 0{,}024R \qquad (R^2 = 0.81) \tag{2}$$

Figure 3 shows an example of the correlations between the dependent variable S and the independent variable of previous model. It is possible to observe the general consistency of the indicator: specifically it assumes higher values for smaller radii where the dynamic of the motorcycle is more subjected to the destabilizing forces; moreover for the same radius considered, the indicator increases when the speed of the motorcycle increases, because higher speed involves greater destabilizing forces and moments; and finally for the same radius and speed, lower the friction coefficient (higher the polishing damage) higher the indicator. In Figure 3, for the braking force of 80N, the indicator S is represented in relation with vehicle speed, horizontal curve radius and friction coefficient.

For the values of the independent variables (μ, V, R, F) that caused the fall of the motorcycle (see red line in Figure 2), the model provides the limit value (S_{limit}) of the dependent variable in these falling conditions. Referring to these limit values it was possible to define "% of limit value" of the indicator that identify combinations of variables that determine for example the 75% or 50% of limit value. Such percentages of S_{limit} allowed to divide the no fall area into several areas where the configurations of independent variables determine different severity of risk conditions.

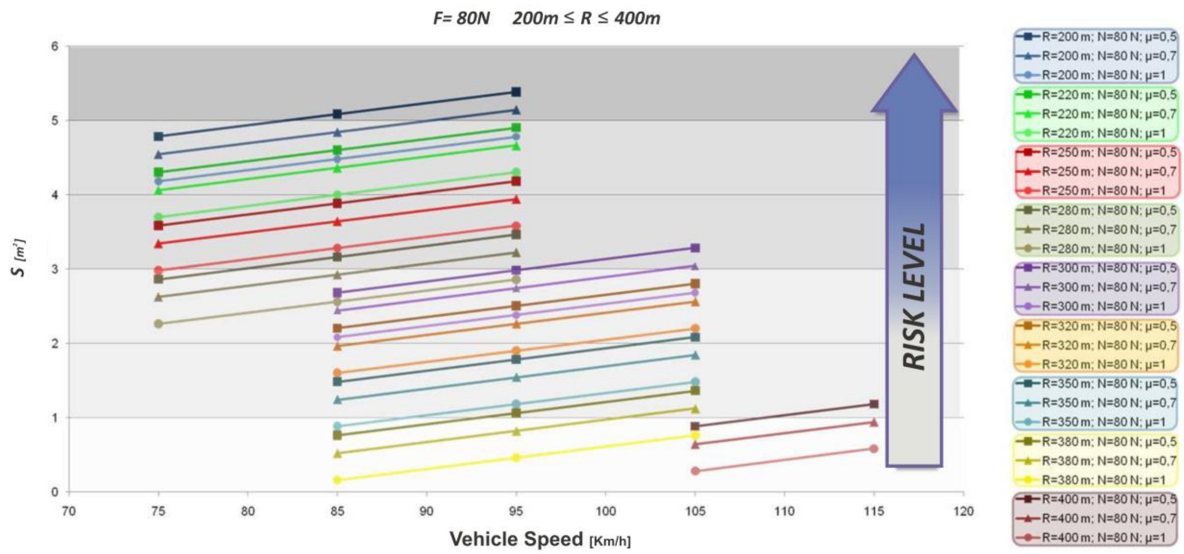

Fig. 3. Indicator values for F= 80 N

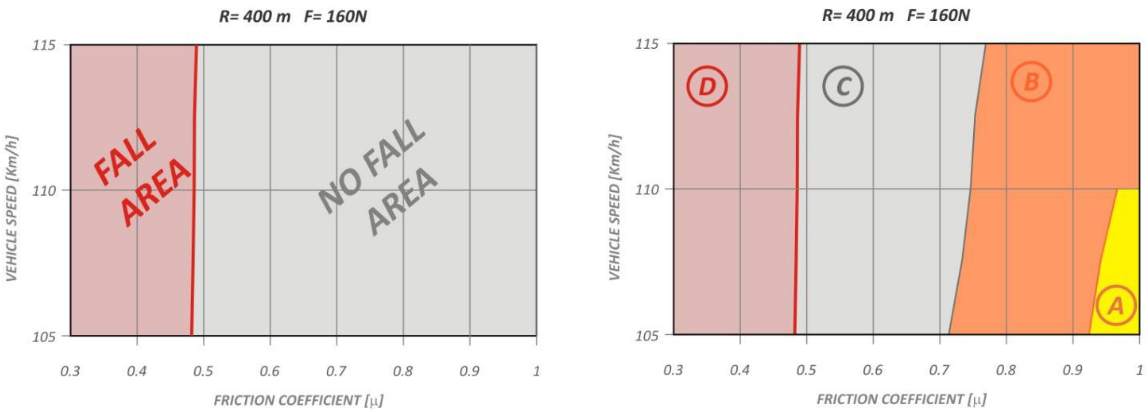

Fig. 4. Comparison between diagrams for R=400m and F= 160 N

Figure 4 shows an example of the diagram with R=400 m and F=160N. On the left we have the diagram obtained with the results of the first phase of the analysis, while on the right it is possible to see how the no fall area is divided into several area bordered by different percentage of limit S value. Specifically:

- A is the area where indicator S is lower than 50% of its limit values;
- B is the area where indicator S has a value between 50 and 75% of its limit values;
- C is the area where indicator S has a value between 75 and 100% of its limit values;
- D is the fall area.

5. Conclusions

The present study investigated the effects of a typical road pavement damage, the polishing of aggregates, on motorcycle stability and consequently on the safety of rider driving. The authors used a numerical simulation approach based on BikeSim dynamic simulation code, which allowed to analyze the effects of polishing, represented with different friction levels on the dynamic behaviour of motorcycles under different driving conditions characterized by different motorcycle speeds and decelerations along different curve radii.

Based on the outcomes of these simulations the most significant variable for describing the effect on dynamic of the motorcycle is identified and a predicting model of the dynamic behaviour of motorcycle is proposed.

These results can be considered as the first step for a new developing programming maintenance interventions. In fact an useful tool for planning maintenance interventions is proposed taking into account the risk associated to the asphalt polishing of the pavement. Such tool, once implemented with the results of the research on several other pavement defects, could allow the managing agencies to identify the priorities of the maintenance interventions in relation to the safety of driving.

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